Regional Variations of µTBS of Light- and Chemically-cured Resin Composite Restorations in Clinically Relevant Situations

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Purpose: To test whether the distance to the mass center of a buildup made of visible-light- or chemically curing composite resin bonded to dentin and cured in one increment has an influence on µTBS.

Materials and Methods: In the experimental groups, one-increment visible-light (Z250) or chemically-cured (TiCore) composite-resins buildups were bonded to flattened bovine dentin surfaces. In the control groups, the same materials were bonded as separate buildups on circumscribed areas to minimize the effect of shearing polymerization contraction. Compound composite/interface/dentin specimens were trimmed out of buildups and tested in tension until detachment; the distances to the mass centers of their respective buildups were recorded as the independent variable. The correlation between µTBS and distances was tested in each group. Slopes and intercepts of regression lines (µTBS to bonded area) were compared in the experimental groups.

Results: The correlation between µTBS and distances was negative and statistically significant for both experimental groups ($p < 0.0001$), but not for the two control groups ($p > 0.34$).

Conclusion: In clinical situations such as direct resin veneering or resin core construction, where a first layer of a light- or chemically cured resin composite is bonded and cured on a broad surface, the µTBS of the interface decreases proportionally to the distance to the mass center of the restoration.

Keywords: polymerization shrinkage, polymerization stress, resin composite, regional bond strength, microtensile testing.

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Stress within dental curing composite resins is not a material property, but a local physical state, derived from the combination of material properties, direction and intensity of curing light, spatial distribution of restoration and complementary bonded surfaces, and boundary conditions.[3,15,17,38,69,71]

It has been shown that the ultimate tensile bond strength of resin composites bonded to dental tissue changes with regions in the cavity walls[50] due to polymerization shrinkage. In FEA studies, a triaxial distribution of polymerization contraction stresses has been shown. In cases of minimum compliance, the magnitude of intermediate stresses were calculated parallel to the bonded interface. Similar analyses calculated shear stresses, also distance-related,[4,29,33,39] in the vicinity of bonded interfaces.[54]

Since its introduction in dental research,[62] microtensile bond strength (µTBS) testing has become a routine method for assessing the bond strength of an interface.[1] Some of its advantages are that it can be used to evaluate and compare different areas of same tooth, and that its results are closer to the real adhesive strength, because bonded area (BA) is minimized, hence minimizing the effect of defects in the interface.[1]

However, it has important limitations: results very much depend on the preparation protocol, either in the form of compound slabs or sticks,[30,60] on the dimensions and shape of the BA,[1,28,48,56] and on the method of fixation of specimens before submitting them to stress.[23,70] In addition, although many readings are acquired from an individual specimen or tooth, they are interrelated and should not be statistically considered as independent measurements.[21,44,59]

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One of the most commonly used methods to test µTBS consists in building up a simulated restoration, bonded to a ground or flattened dentin or enamel surface of an extracted human (or other animal) tooth.[64] Such exposed surfaces can be very extensive, for instance, the frequently used transversal section of a molar at the level of the amelodentinal junction.[67]

Afterwards, the bonded assembly is sectioned in one or two planes perpendicularly to the bonded interface, yielding up to 7 slabs per specimen[2] or between 8 and 30 compound sticks or bars[27,44,66,67] to be tested.

It has been experimentally shown that the interfacial µTBS of elongated composite resin buildups bonded to an enamel surface and cured in one increment correlates with the distance from the mass center of the restoration.[10] It has been suggested that this correlation may be due to centripetal displacements of the restorative components of the interface (bonding agent, restorative material). This would happen while curing is incomplete and the flow towards the mass center of the restorative material is still possible, thus destabilizing the hybrid layer when it is still immature.[10,19,31]

Such strain may be the source of the disk deflection that is detected with the deflecting disk method of polymerization contraction measurement.[71] Stress of this nature has been experimentally shown[16] and seems to contribute to marginal defect formation in some direct and indirect restorations.[26,36,37]

In many clinical situations, a relatively large amount of resin is bulk cured and bonded to an extensive dentin area. For example, this may be the case in cementation of a ceramic or resin veneer, during a direct composite veneer placement, in the course of building up a prosthetic bonded-composite resin core, or throughout endodontic obturation with a plastic resinous material.

Using extensive dentin areas as the bonding substrate, some studies have reported differences in µTBS among distinct areas of the interface.[27,44,47,51,57,72,75,77] Such differences may certainly be caused by variations in morphology or the spatial organization of the bonding substrate, but the contribution of shearing movements – as described above – should not be underestimated.

The hypothesis tested here is that (a) when a substantial dentin area is bonded to a composite resin that must be polymerized (ie, that will contract), such polymerization contraction will reduce the quality of the bonded interface's mechanical properties and (b) the quality reduction will increase with distance from the mass center of the curing resin towards the outer boundaries of the bonded interface.

The purpose of this study was to determine the existence and magnitude of the proposed phenomenon in light- and chemically curing restorative materials bonded to extensive dentin areas. Control groups were also examined, in which the phenomenon can be considered negligible, as small, randomly distributed resin-bonded buildups were cured to control for the influence of variations in the adhesive substrate.

MATERIALS AND METHODS

Following the guidelines of the Animal Research Committee of Complutense University, 14 sound bovine incisors were collected and stored until use in distilled, pure water at room temperature for a maximum of one month after extraction.

Preparation of Teeth and Restorations (Fig 1)

Roots were removed ca 1 mm apical to the cementoenamel junction with a water-cooled diamond saw (3031 CP/N Exakt; Norderstedt, Germany). A flat dentin surface was produced on the labial surface of each incisor's crown by wet grinding in a grinder-polisher (Struers Dap-7; Rodøvre, Denmark) with 500-grit SiC paper to achieve a standardized bonding substrate.

Teeth were randomly assigned to one of four experimental groups (Table 1). In the experimental groups VLC1 (visible-light curing, Filtek Z250) and CC1 (chemically curing, Ti-Core), the two restorative composite resins were built up to a height of 2 mm and bonded. In VLC1, the buildup was evenly cured (Optilux 501, Demetron/Kerr; Orange, CA, USA, 800 mW/cm^2) in one increment over the maximum available dentin surface. The curing tip was placed as close as possible to the material being cured but without contact. In CC1, the composite resin was allowed to cure also in one increment, once both components were adequately mixed.

In the control groups VLC2 and CC2, buildups of ca 2 x 2 x 2 mm were bonded as in the corresponding experimental groups, but restricted to randomly selected sites of exposed dentin (up to seven sites per restoration). All precautions were taken to avoid contact between the buildups. Such sites were selected from a mesh that was superimposed on the exposed dentin area.

In all groups, buildups were prepared at least 0.5 mm short of surrounding enamel, to guarantee that bonding was restricted to dentin. All restored teeth were stored for 24 h in a 100% humidity chamber until sectioning to allow completion of curing.

Specimen Preparation and µTBS Testing

The restored teeth of all groups were sectioned (3031 CP/N Exakt) perpendicularly to the bonded interface in two planes to produce rectangular compound composite resin-dentin specimens. Their bonded areas (BA) in mm^2 were measured with a digital caliper (Mitutoyo SPC, Mitutoyo; Tokyo, Japan) exact to 0.01 mm. Specimens were fixed (Superglue 3, Loctite; Madrid, Spain) to a rigid tensile testing device. Once affixed, glue was added to their lateral aspects. Then the adhesive joints were submitted to tension (Hounsfield HTI 500N; Croydon, UK) at a crosshead speed of 1 mm/min until failure.

Subsequently, the debonded areas were observed (40X) with a stereoscopic microscope (Leica MZ12, Leica Imaging Systems; Cambridge, UK) to determine the type of fracture (adhesive, cohesive, or mixed). Only adhesively debonded specimens were included in the analysis. µTBS (MPa) was calculated.

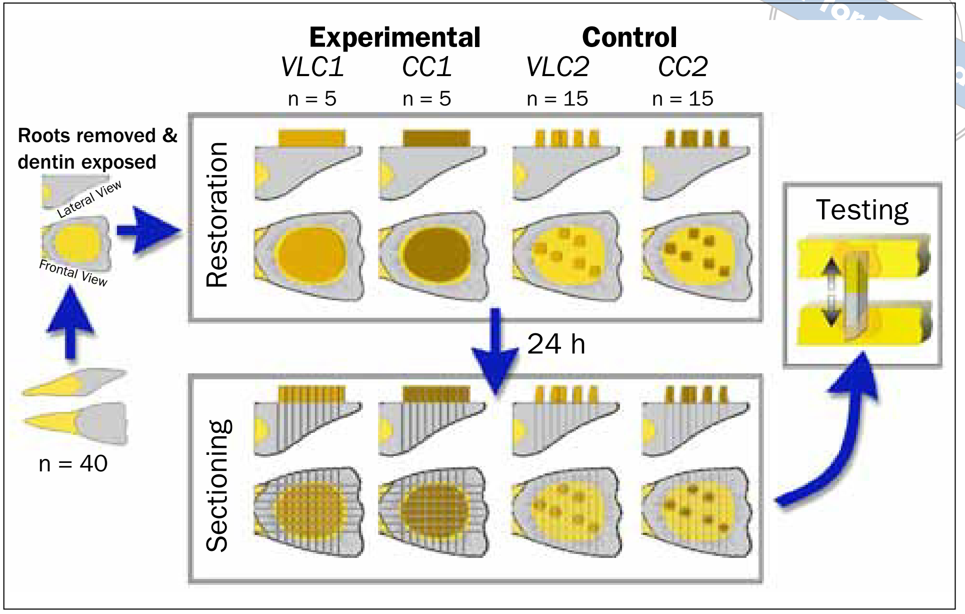

Fig 1 Preparation of teeth, restorations, sectioning, and testing of specimens. VLC: visible-light curing; CC: chemically curing.

Table 1 Materials used and group assignment

Polymerization	Visible-light curing		Chemically curing	
Group	VLC1 e	VLC2 c	CC1 e	CC2 c
No. of teeth	5	15	5	15
Restorative	Filtek Z250, 3M-ESPE; St Paul, MN, USA. Batch # 20030414		Ti-Core, Essential Dental Systems; Hackensack, NJ, USA. Batch # 071107	
Adhesive	Adper Scotchbond 1 XT, 3M-ESPE. Batch # 174213 (Single Bond in USA)		Adper Scotchbond MP, 3M-ESPE. Activator Adper Scotchbond 1.5 batch # 20080627. Primer Adper Scotchbond 2, batch # 20080806. Adper Scotchbond 3 batch # 20080806 admixed with catalizer Adper Scotchbond 3,5 batch # 20080716.	

e : experimental, c: control.

Calculation of the Dependent Variable PTens

The specimens were not manipulated further after sectioning and there were no additional refinements of BA. They were rectangular in shape, directly obtained by trimming, with a BA mean (SD) of 0.78 (0.29) mm^2. Such fluctuations made it advisable to adjust each μTBS value to the specific BA on which it was based to exclude bias due to BA differences.

For this, a μTBS (in MPa) to BA (in mm^2) regression curve of results of all valid specimens (pooled experimental and control groups) was calculated using the LSD (least squares differences) method (IBM SPSS Statistics v.19, SPSS; Chicago, IL, USA). This was based on the idea that if the μTBS results of all specimens had been determined by BA alone (with no influence of their individual distances to the mass center of its tooth), all of them would then have been exactly aligned on this regression line. However, the present data did not behave in this manner. The difference between the actual μTBS values and the regression line of the μTBS ("residuals", in MPa) were considered to be caused by factor(s) other than BA. In this study, such residuals are considered the outcome, as they were hypothetically related to the distance of specimens to the mass center of the restoration whence they originated.

Additionally, it is possible that μTBS evaluation of the bovine teeth used in this research resulted in consistently higher (or lower) values because of some unidentified, individual characteristic of the dentin, such as its (micro) structure, calcification, or age of the animal. Because this study deals with variations in residuals within each bonded surface caused by the independent variable (distance to the center of the mass of the restoration), only increases or decreases of bond strength relative to same bonded surface are considered.

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Therefore, residuals were transformed into fractional ranks (in %) – the dependent variable, termed PTens – within each restored tooth by the formula PTens = 100 x R/MaxR, where R is the residual for that case, and MaxR the maximum residual for that case.

Calculation of the Independent Variable PDist

In VLC1 and CC1 experimental groups, the distance of each specimen to the mass center of its restoration was directly recorded from the trimmed restorations as the horizontal distance of the center of each specimen along its major axis to the mass center of its restoration.

In VLC2 and CC2 control groups, specimens were trimmed out from separate composite resin build-ups, prepared at randomly selected positions: there was no real mass center. The distances of specimens were defined as the distance of their centers to a mean theoretical mass center of restorations in these groups, as if all restorations had the same extension and profile as the mean extension and profile of those in experimental groups.

Exposed dentin areas of all teeth had different sizes. For this reason, resin buildups in experimental groups and theoretical restorations in control groups had diverse sizes and resulted in a different number of specimens when sectioned.

The hypothesized effect is assumed to be distance-related; therefore, in all groups, distances of each specimen to the mass center (or theoretical mass center, in control groups) of its restoration were transformed into fractional ranks (in %) – the independent variable PDist – with the formula: PDist = 100 x D/MaxD, where D is distance of the center of the specimen to the mass center of the restoration, and MaxD the maximum distance of the corresponding restoration.

Evaluation and Comparison Between Groups

To determine whether there was a correlation between PDist and PTens, Pearson's correlation test (r, coefficient of correlation) and its 95% confidence interval (CI) was calculated for each group.

To compare the levels of the effect between VLC1 and CC1 groups by polymerization mode (VLC1, visible-light curing; CC1, chemically curing), a comparison of intercepts and slopes of the regression lines was done (Statgraphis+ 5.0, Statistical Graphics; Warrenton, VA, USA).

To compare the levels of the effect between experimental and control groups at the outermost margins of restorations, a nonparametric Mann-Whitney U-test of was performed between PTens values of the 10% highest PDist of each group.

Relationship Between Distance and Pre-test Failures

If the hypothesized effect was present, a relationship between the number of pre-test failures (PTFs) produced during trimming or preparation of specimens and PDist could be expected. If the μTBS of specimens were reduced in any way by high levels the hypothesized effect (at the outer limits of restorations) PTFs could be expected in higher proportions than specimens exposed to lower levels of the effect (ie, those located near the mass center of the restoration).

To examine this, only PTFs were included with a known reason for failure which could be logically attributed to a decreased interfacial TBS. These were only PTFs produced during trimming or preparation.

To determine whether there is an association between PTF proportions and PDist, the Mantel-Haenszel test for linear-by-linear association between proportions was used. Due to requirements of the test, PDist as the independent variable was classified into 5 categories (0% to 20%, 21% to 40%, 41% to 60%, 61% to 80%, 81% to 100%). PTF proportions in each category were compared.

RESULTS

μTBS and Distances

The mean BA was 0.78 mm^2 (SD = 0.29). The relationship of μTBS test results of all valid specimens (all groups pooled) to their BA values was found to be logarithmic (Fig 2), according to the equation

$\mu TBS = 21.8 - 16.3 \cdot Ln(BA)$,

with the μTBS in MPa and BA in mm^2. ANOVA showed the relationship to be significant, with $p < 0.0001$ ($r^2 = 0.26$).

In total, 775 specimens were produced (Table 2). The distance on the y-axis of the actual specimens' μTBS values to the common regression line (regression's residuals, in MPa) were transformed into fractional ranks (in %) – the dependent variable PTens – within each restored tooth. The distance of each valid specimen to the mass center (or theoretical mass center) of its restoration was transformed into a fractional rank (in %) – the independent variable PDist – as mentioned in the previous section. The distributions of PTens to PDist by group are shown in Fig 3.

Assessment of the Effect and Comparison Between Groups

Pearson's correlation test (r, coefficient of correlation; 95% CI) results are shown in Table 3. The correlation between PTens and PDist was statistically significant in the experimental groups (VLC1 and CC1, $p < 0.0001$ in both). This correlation was negative: the higher the PDist value, the lower the PTens, thus confirming the test hypothesis (Fig 3). In the control groups (VLC2 and CC2), this correlation was also negative but not statistically significant ($p = 0.99$ and 0.34 respectively, Table 3). Significance is also shown through Pearson's r and 95% CI intervals: in VLC1 and CC1 groups they do not overlap zero values, but in VLC2 and CC2 groups they do.

The comparison of intercepts and slopes of the regression lines (Table 3 and Fig 3) between VLC1 and CC1 groups was not significant (for the intercepts, $p = 0.48$ and for the slopes, $p = 0.44$): between experimental groups, variations of PTens values were not statistically significant at the centers of restorations, where PDist = 0 (intercepts). For these groups, the decline of PTens values exhibited the same slopes when distances to the mass centers of restorations increased.

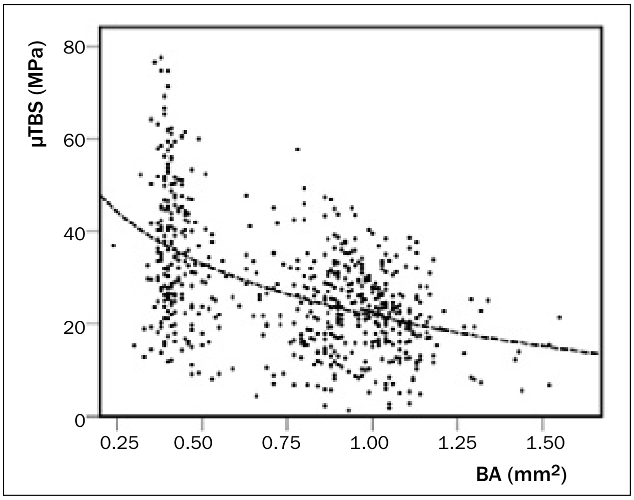
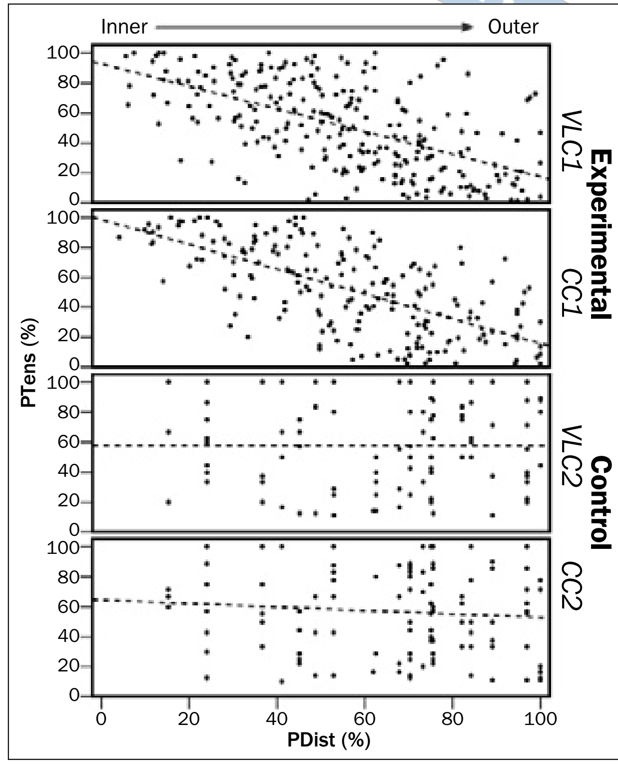


Fig 2 Regression of µTBS (MPa) test results to BA (mm²) of all pooled valid specimens. Logarithmic regression line formula: µTBS = 21.8 – 16.3·Ln(BA).

Fig 3 Fractional ranks of residuals to regression line in Fig 2 (PTens dependent variable, in %) plotted against distances of each specimen to the mass center (or theoretical mass center) of its specimen, transformed to fractional ranks within their restoration (PDist independent variable, in %) per group.



The results comparing PTens values of the 10% highest PDist of each material group were significantly different, with p = 0.004 for the visible-light curing material and p = 0.012 for the chemically curing material (Mann-Whitney U-test). Decreases in PTens values were significant for both light-curing and chemically curing materials if the restorations were placed and cured in one increment (experimental groups), compared to the situation where the hypothesized effect was not present (control groups) for the same manner of polymerization.

Relationship Between Distances and PTF Proportions

The numbers of PTFs and valid specimens are shown in Table 2. The Mantel-Haenszel linear-by-linear test showed that the proportions of PTF specimens linearly increased with PDist category in experimental groups (Table 3). This increase was statistically significant ($p < 0.0001$ for both groups). In control groups, proportions did not change significantly: in VLC2, p = 0.67; in CC2, p = 0.3.

DISCUSSION

A hypothesized centripetal shearing effect of polymerization contraction of composite resins was tested in this study. This effect would hypothetically cause a decrease of µTBS ranging from a minimum at the specimen's center to a maximum at the outer limits of the restoration.

Bovine incisors were used because their dentin has proven similar to human for microtensile

Table 2 Number of valid specimens and pre-test failures per PDist category

Group			Valid	PTF				Total
				S	P	C	U	
VLC1	PDist category	1	57		7			64
		2	58	2	6			66
		3	56	2	9			67
		4	45	4	16			65
		5	36	9	20			65
	Total		252	17	58			327
CC1	PDist category	1	44					44
		2	44	1	2			47
		3	39	3	2			44
		4	43	4				47
		5	31	11	3			45
	Total		201	19	7			227
VLC2	PDist category	1	13					13
		2	23		2			25
		3	21	2		1		24
		4	20	1	1			22
		5	18		1			19
	Total		95	3	4	1		103
CC2	PDist category	1	16					16
		2	28				1	29
		3	26					26
		4	23	2		1	1	27
		5	19			1		20
	Total		112	2		2	2	118

Reasons for pre-test failures (PTF): S: sectioning, P: preparation, C: cohesive fracture, U: unknown.

Table 3 Results of statistical analyses

Group	Correlation PTens to PDist		Regression PTens to PDist		Significance (p) of PTF proportions according to Mantel-Haenszel test
	Pearson's r	Significance of correlation (p)	Intercept	Slope	
VLC1	-0.59	< 0.0001*	92.9	-0.76	< 0.0001*
CC1	-0.66	< 0.0001*	98.5	-0.83	< 0.0001*
VLC2	-0.001	0.99	-	-	0.67
CC2	-0.09	0.34	-	-	0.3

* Statistically significant.

testing.[12,13,20,32,43,49,65,72,74] It has been widely used for the analysis of polymerization contraction stresses[8,10,18,25,32,39,40,45,46,53] and µTBS testing.[6,10,41,58] In addition, larger areas of exposed dentin, such as the ones obtained from these teeth, allowed for an augmentation of the hypothesized effect.

Experimental groups contained five teeth each, as opposed to control groups, where fifteen teeth each were used. These differences were intentional: in control groups, fewer specimens were obtained per tooth (between four and seven), as they were trimmed from separate buildups. In order to compare possible effects due to polymerization mode, two different resin composites were used, one visible-light (VLC1 and VLC2) and one chemically curing (CC1 and CC2), corresponding to two common clinical situations.

A relationship has been described between µTBS and polymerization contraction shrinkage[35] and between the modulus of elasticity of a material and polymerization shrinkage.[61] Despite the important differences in the modulus of elasticity of materials used in this study (11.5 GPa for Z250,[22] 6.1 GPa for TiCore[14]), neither differences in intercept nor in slopes of their regression curves (PTens to PDist, Fig 3) were statistically significant. In this study, the hypothesized effect was present, but the modulus of elasticity of the materials apparently did not produce noticeable differences.

An FEA study on polymerization contraction stresses in resin composite restorations[39] predicted shearing stresses appearing in the bottom of a rectangular cavity, increasing in importance as the distance to the center of the cavity increased. Although differences between configurations in that study (rectangular cavity with a C-factor of 3.8, and bonded lateral walls) and in the current report (resin buildups with an approximate C-factor of 0.53) must be considered, the presence and characteristics of the mentioned shearing stresses could explain the distance-related effect found in our study. Similar stresses have been described by other authors,[4,29,33,42,73] although the configuration factors there were also different from that of this study.

The two materials were bonded using different bonding systems (Scotchbond 1 XT for VLC1 and VLC2, Adper Scotchbond MP for CC1 and CC2, Table 1). In the former, a visible-light curing material was needed, and in the latter a chemically cured one. To test whether this caused differences in µTBS between chemically and visible-light curing materials, PTens ranks were compared between VLC1 and CC1 materials placed in central positions (PDist equal to or lower than 50%, to select specimens placed in similar dentin). With these restrictions, the mean (SD) for VLC1 was 69.6 (23.2) MPa, and for CC1 73.1 (22.4) MPa, with 100 and 78 specimens, respectively; thus, the ranks were not statistically significantly different ($p = 0.29$). Apparently, differences in adhesives did not cause statistically significant differences between PTens of the materials in the experimental groups.

One of the advantages of the microtensile test is that it minimizes and allows a certain measure of control over the influence of the BA size on the results.[62] It has been shown that BA variations produce differences in µTBS results. The interrelationship between BA and µTBS has been described as following logarithmic,[62] linear,[55] inverse,[24] or exponential[68] distributions. BA differences among specimens in this study were not refined or in any way modified after trimming. To prevent the bias that such differences would have produced, µTBS results (in MPa) were transformed to residuals to the BA/µTBS regression line. Later, the PTens dependent variable was calculated by means of a percentage rank transformation. In this way, all specimens (of all BAs) of all teeth (of all extents of bonded dentin) were comparable.

However, this method of balancing the influence of BA on µTBS has undesirable consequences: direct clinical interpretation of µTBS results by themselves becomes very difficult. However, the interpretation of its relationship to PDist is straightforward: the higher the distance to the center of the restoration, the lower the µTBS value.

To make results comparable to other reports, µTBS values are given (Table 4) for those specimens placed in central positions (PDist lower or equal to 50%), with BAs between 0.9 and 1.1 mm^2. A comparable value was reported for one of the adhesives used, Adper ScothBond 1 XT, 35.6 (4.2) MPa, using a BA range from 0.73 to 0.78 mm^2.[25] A review of µTBS results using different test methods reported 36.1 (10.4) MPa,[65] but no information is given on BA size used. Other studies reported 40.11 (15.68) MPa using 0.42 mm^2 BA,[26] and 48.4 (8) MPa[66] or 49.6 (13.9) MPa[22] using BA of 0.8 mm^2. For the other

Table 4 μTBS values (MPa) for specimens in central positions (PDist lower or equal to 50%), with BA between 0.9 and 1.1 mm²

Adhesive	Group	n	m	SD
Adper SB 1 XT	VLC1	4	31.7	2.4
	VLC2	17	21.5	1.7
Adper Scotchbond MP	CC1	24	25.2	2
	CC2	13	26	1.4

n: number of specimens, m: mean, SD: standard deviation.

adhesive used – Adper ScothBond MP – μTBS values of 3.9 (1.3) MPa using a BA = 25 mm^2, 36.01 (8.4) MPa using a BA of 1.08 mm^2, or 20.01 MPa using a BA of 1.1 mm^2 or a median μTBS result of 52.7 MPa using a BA of 2.25 mm^2 have been reported by Betarmar et al,[5] Burrow et al,[9] and Bortolotto et al,[7] respectively.

Pearson's regression coefficient of μTBS results to BA of all pooled, valid, specimens was significant ($p < 0.0001$), although the relationship was weak ($r^2 = 0.26$) (Fig 2). Reasons for this low value could be intrinsic variability, or because the two variables – namely, BA and the independent variable PDist – are mixed in the analysis, and PDist acts as a confounding factor, as the regression was calculated only for BA. As an example, regression was calculated for each group separately, and Pearson's r^2 coefficients were different (VLC1 = 0.09, CC1 = 0.1, VLC2 = 0.4, CC2 = 0.3). It can be seen that if adjustment of μTBS for BA is performed independently for control groups, in which the hypothesized effect is not present (VLC2 and CC2), the coefficients are at least three times higher than in the experimental groups (VLC1 and CC1, in which it is supposed to be present).

Yet another consequence of this transformation is a relative augmentation of variation in results. The relationship between PTens and PDist shows considerable dispersion of PTens data according to material (Fig 3). Such variability is probably increased by the transformation of μTBS values to the PTens variable. This transformation into percentages causes the maximum μTBS value of each tooth to transform into 100% PTens and the other μTBS values to vary accordingly. As a result, high dispersion of PTens values is observed. However, the correlation is strong enough in experimental groups to be statistically significant.

In addition, transformation of the distance of specimens to the mass center of their restorations to PDist was required. Distances of the center of specimens to the mass center of the restoration were transformed into fractional ranks and given in percentages, producing the independent variable PDist. Exposed dentin surfaces were dissimilar in size, thus allowing for the construction of buildups having different total bonded areas. All efforts were made to produce 2-mm-high buildups in all cases. For this reason, two theoretical specimens having the same absolute distances to mass centers of their restorations would have been considered identical, but the extent of the hypothesized effect would have been different. It would depend not only on the distance to the mass center (the same for both), but also on the amount of material located between each specimen and the external margins of corresponding restorations measured along both lines passing through mass centers and specimens' centers, which may have exerted an opposing effect.

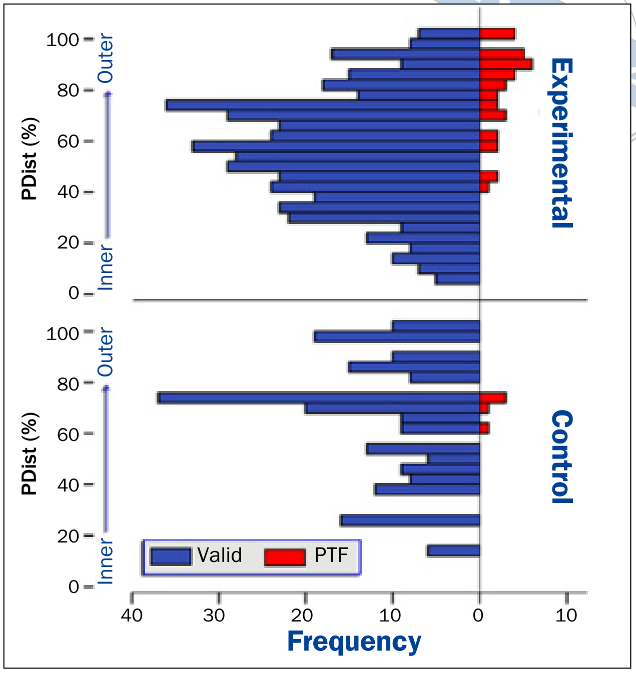


Fig 4 Distribution of frequencies of valid specimens and pre-test failures (PTF) along PDist category, per group.

It must also be considered that peripheral specimens, not having a rectangular BA shape when trimmed, were discarded. In this way, specimens accounted as extremes were really not placed in the outermost positions in their restorations, which would contribute to increased dispersion.

Each restoration produced several specimens. The interrelationship of various measurements from one sample (tooth) is a concern[21,44,59] only if they are considered independent. In this study, this is not the case, as the effect that a specimen's distance to its mass center may have on its μTBS results was assessed. This effect is particularized for each specimen, since dependent and independent variables (PTens and PDist) are transformed to percentage values within their restorations.

An analysis of the relationship between PDist and the PTF proportions of specimens has been reported previously,[27] and yields supporting evidence of correlation. If the Mantel-Haenszel test shows statistical significance, as is the case for experimental groups, its interpretation is that increases in one variable (PTF proportions) are associated with constant increases in the other (PDist category) greater than would be expected by chance. PTF proportions with respect to valid specimens significantly increase when approaching to restoration boundaries in experimental groups (Fig 4, Table 2).

This could also be an effect of differences in substrate. In the center of the restorations, higher μTBS is to be expected, because the exposed dentin's physical characteristics at those locations is more favorable for adhesion.[11,34,44,47,63,65,77] Hence, a decrease of μTBS is obtained in the outer part of exposed dentin surfaces. However, our results showed that the correlation of PTens and PDist is negative but not significant in control groups: Pearson's r in VLC2 group is -0.001 ($p = 0.99$), and in CC2 group is -0.09 ($p = 0.34$). Both experimental groups (VLC1 and CC1) showed also a negative, but significant correlation (Pearson's coefficients were 0.59 and 0.66, both having $p < 0.0001$).

The behavior of PTF was similar (Fig 4). The Mantel-Haenszel test results showed that for the experimental groups, the proportion of PTF significantly (for both, $p < 0.0001$) increased with PDist. This did not happen for control groups ($p = 0.67$ and 0.3, respectively) (Table 3). This also supports the idea that centripetal stresses due to polymerization contraction of composite resins are a probable cause of defects at the margins of large direct resin-bonded restorations.

Pre-test failures were not included in the statistical analysis of μTBS. From our hypothesis, shearing stresses towards mass centers disrupted the immature interface, causing PTFs in proportions that increased toward the outer limits of the bonded area. We excluded them because assigning them a zero value would have been unrealistic: most likely, specimens debonded because their resistance was very low, but not zero, and because including such extremely low values would imply that they were expected values, which would also have been also inaccurate.

As mentioned above, some studies have reported differences in μTBS between central and peripheral measurements, when measured on extensive dentin areas, but the results are inconclusive.[27,44,47,51,52,57,62,66,67,72,75,77,78] Possible reasons for this, other than local differences in dentin, can be that BAs were not controlled in these reports, that an enamel band at the periphery of the dentin bonding area was allowed, which would produce a counteracting effect, that few specimens were produced, and probably most important, that the relationship between distance and μTBS has not yet been systematically examined.

CONCLUSION

The results of this study indicate that composite resin restorations of extended areas, eg, direct resin veneers or core buildups, may experience a decrease of bond strength at their periphery if they are built up as a single increment which covers the whole area to be bonded.

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REFERENCES

1. Armstrong S, Geraldeli S, Maia R, Raposo LHA, Soares CJ, YamagawaJ. Adhesion to tooth structure: A critical review of "micro" bond strength test methods. Dent Mater 2010;26:e50-e62.
2. Armstrong SR, Boyer DB, Keller JC. Microtensile bond strength testing and failure analysis of two dentin adhesives. Dent Mater 1998;14:37-43.
3. Asmussen E, Peutzfeldt A. Direction of shrinkage of light-curing resin composites. Acta Odontol Scand 1999;57:310-315.
4. Barink M, van der Mark PC, Fennis WM, Kuijs RH, Kreulen CM, Verdonschot N. A three-dimensional finite element model of the polymerization process in dental restorations. Biomater 2003;24:1427-1435.
5. Betamar N, Cardew G, van Noort R. The effect of variations in hourglass specimen design on microtensile bond strength to dentin. J Adhes Dent 2007;9:427-436.
6. Betamar N, Cardew G, van Noort R. Influence of Specimen Designs on the Microtensile Bond Strength of Dentin. J Adhes Dent 2007;9: 159-168.
7. Bortolotto T, Mileo A, Krejci I. Strength of the bond as a predictor of marginal performance: An in vitro evaluation of contemporary adhesives. Dent Mater 2010;26:242-248.
8. Braga RR, Boaro LC, Kuroe T, Azevedo CL, Singer JM. Influence of cavity dimensions and their derivatives (volume and ‚C' factor) on shrinkage stress development and microleakage of composite restorations. Dent Mater 2006;22:818-823.
9. Burrow MF, Thomas D, Swain MV, Tyas MJ. Analysis of tensile bond strengths using Weibull statistics. Biomater 2004;25:5031-5035.
10. Cabrera E, de la Macorra JC. Polymerization shrinkage influences microtensile bond strength. J Dent Res 2007;86:227-231.
11. Cagidiaco MC, Ferrari M, Vichi A, Davidson CL. Mapping of tubule and intertubule surface areas available for bonding in Class V and Class II preparations. J Dent 1997;25:379-389.
12. Calheiros FC, Sadek FT, Braga RR, Cardoso PEC. Polymerization contraction stress of low-shrinkage composites and its correlation with microleakage in class V restorations. J Dent 2004;32:407-412.
13. Camargo MA, Marques MM, de Cara AA. Morphological analysis of human and bovine dentine by scanning electron microscope investigation. Arch Oral Biol 2008;53:105-108.
14. Combe EC, Shaglouf AMS, Watts DC, Wilson NHF. Mechanical properties of direct core build-up materials. Dent Mater 1999;15:158-165.
15. Chiang YC, Rösch P, Dabanoglu A, Lin C-P, Hickel R, Kunzelmann K-H. Polymerization composite shrinkage evaluation with 3D deformation analysis from [mu]CT images. Dent Mater 2010;26:223-231.
16. Chiang YC, Rösch P, Lin CP, Hickel R, Kunzelmann KH. Deformation analysis of composite polymerization shrinkage from [mu]CT images. Dent Mater 2009;25:e10-e10.
17. Cho BH, Dickens SH, Bae JH, Chang CG, Son HH, Um CM. Effect of interfacial bond quality on the direction of polymerization shrinkage flow in resin composite restorations. Oper Dent 2002;27:297-304.
18. Choi KK, Ryu GJ, Choi SM, Lee MJ, Park SJ, Ferracane JL. Effects of cavity configuration on composite restoration. Oper Dent 2004;29:462-469.
19. Davidson CL, de Gee AJ, Feilzer A. The competition between the composite-dentin bond strength and the polymerization contraction stress. J Dent Res 1984;63:1396-1399.
20. de Goes MF, Giannini M, Foxton RM, Nikaido T, Tagami J. Microtensile bond strength between crown and root dentin and two adhesive systems. J Prosthet Dent 2007;97:223-228.
21. Eckert G, Platt J. A statistical evaluation of microtensile bond strength methodology for dental adhesives. Dent Mater 2007;23:385-391.
22. Eick JD, Kotha SP, Chappelow CC, Kilway KV, Giese GJ, Glaros AG, et al. Properties of silorane-based dental resins and composites containing a stress-reducing monomer. Dent Mater 2007;23:1011-1017.
23. El Zohairy AA, de Gee AJ, de Jager N, van Ruijven LJ, Feilzer AJ. The Influence of specimen attachment and dimension on microtensile strength. J Dent Res 2004;83:420-424.
24. Escribano NI, Del-Nero MO, de la Macorra JC. Inverse relationship between tensile bond strength and dimensions of bonded area. J Biomed Mater Res B Appl Biomater 2003;66:419-424.
25. Ferracane JL, Mitchem JC. Relationship between composite contraction stress and leakage in Class V cavities. Am J Dent 2003;16:239-243.
26. Frankenberger R, Krämer N, Lohbauer U, Nikolaenko SA, Reich S. Marginal Integrity: Is the Clinical Performance of Bonded Restorations Predictable In Vitro? J Adh Dent 2007;9:107-116.
27. Gamborgi GP, Loguercio AD, Reis A. Influence of enamel border and regional variability on durability of resin-dentin bonds. J Dent 2007; 35:371-376.

28. Ghassemieh E. Evaluation of sources of uncertainties in microtensile bond strength of dental adhesive system for different specimen geometries. Dent Mater 2008;24:536-547.
29. Goncalves F, Pfeifer CSC, Meira JBC, Ballester RY, Lima RG, Braga RR. Polymerization stress of resin composites as a function of system compliance. Dent Mater 2008;24:645-652.
30. Goracci C, Sadek FT, Monticelli F, Cardoso PEC, Ferrari M. Influence of substrate, shape, and thickness on microtensile specimens' structural integrity and their measured bond strengths. Dent Mater 2004;20:643-654.
31. Hashimoto M, de Gee AJ, Feilzer AJ. Polymerization contraction stress in dentin adhesives bonded to dentin and enamel. Dent Mater 2008;24:1304-1310.
32. He Z, Shimada Y, Tagami J. The effects of cavity size and incremental technique on micro-tensile bond strength of resin composite in Class I cavities. Dent Mater 2007;23:533-538.
33. Hubsch PF, Middleton J, Knox J. A finite element analysis of the stress at the restoration-tooth interface, comparing inlays and bulk fillings. Biomater 2000;21:1015-1019.
34. Huo B. An inhomogeneous and anisotropic constitutive model of human dentin. J Biomech 2005;38:587-594.
35. Ilie N, Kunzelmann KH, Hickel R. Evaluation of micro-tensile bond strengths of composite materials in comparison to their polymerization shrinkage. Dent Mater 2006;22:593-601.
36. Irie M, Suzuki K. Current luting cements: marginal gap formation of composite inlay and their mechanical properties. Dent Mater 2001; 17:347-353.
37. Irie M, Suzuki K, Watts DC. Marginal gap formation of light-activated restorative materials: effects of immediate setting shrinkage and bond strength. Dent Mater 2002;18:203-210.
38. Kahler B, Kotousov A, Borkowski K. Effect of material properties on stresses at the restoration-dentin interface of composite restorations during polymerization. Dent Mater 2006;22:942-947.
39. Kinomoto Y, Torii M. Photoelastic analysis of polymerization contraction stresses in resin composite restorations. J Dent 1998;26:165-171.
40. Kinomoto Y, Torii M, Takeshige F, Ebisu S. Polymerization contraction stress of resin composite restorations in a model Class I cavity configuration using photoelastic analysis. J Esthet Dent 2000;12:309-319.
41. Kitasako Y, Burrow MF, Nikaido T, Harada N, Inokoshi S, Yamada T, Takatsu T. Shear and tensile bond testing for resin cement evaluation. Dent Mater 1995;11:298-304.
42. Koplin C, Jaeger R, Hahn P. A material model for internal stress of dental composites caused by the curing process. Dent Mater 2009;25:331-338.
43. Krifka S, Börzsönyi A, Koch A, Hiller K-A, Schmalz G, Friedl K-H. Bond strength of adhesive systems to dentin and enamel–Human vs. bovine primary teeth in vitro. Dent Mater 2008;24:888-894.
44. Loguercio AD, Barroso LP, Grande RHM, Reisa A. Comparison of Intra- and Intertooth Resin-Dentin Bond Strength Variability. J Adh Dent 2005;7:151-158.
45. Loguercio AD, Reis A, Ballester RY. Polymerization shrinkage: effects of constraint and filling technique in composite restorations. Dent Mater 2004;20:236-243.
46. Loguercio AD, Reis A, Schroeder M, Balducci I, Versluis A, Ballester RY. Polymerization shrinkage: effects of boundary conditions and filling technique of resin composite restorations. J Dent 2004;32:459-470.
47. Loguercio AD, Uceda-Gomez N, Carrilho MR, Reis A. Influence of specimen size and regional variation on long-term resin-dentin bond strength. Dent Mater 2005;21:224-231.
48. Meira J, Souza R, Driemeier L, Ballester R. Stress concentration in microtensile tests using uniform material. J Adh Dent 2004;6:267-273.
49. Mota CS, Demarco FF, Camacho GB, Powers JM. Tensile bond strength of four resin luting agents bonded to bovine enamel and dentin. Journal of Prosthetic Dentistry 2003;89:558-564.
50. Nayif M, Nakajima M, Aksornmuang J, Ikeda M, Tagami J. Effect of adhesion to cavity walls on the mechanical properties of resin composites. Dent Mater 2008;24:83-89.
51. Pereira PN, Okuda M, Sano H, Yoshikawa T, Burrow MF, Tagami J. Effect of intrinsic wetness and regional difference on dentin bond strength. Dent Mater 1999;15:46-53.
52. Pereira PNR, Sano H, Ogata M, Zheng L, Nakajima M, Tagami J, et al. Effect of region and dentin perfusion on bond strengths of resin-modified glass ionomer cements. J Dent 2000;28:347-354.
53. Pereira RA, Araujo PAd, Castañeda-Espinosa JC, Mondelli RFL. Comparative analysis of the shrinkage stress of composite resins. J App Oral Sci 2008;16:30-34.
54. Petrovic LM, Atanackovic TM. A model for shrinkage strain in photo polymerization of dental composites. Dent Mater 2008;24:556-560.
55. Phrukkanon S, Burrow MF, Tyas MJ. Effect of cross-sectional surface area on bond strengths between resin and dentin. Dent Mater 1998;14:120-128.
56. Poitevin A, de Munck J, van Landuyt K, Coutinho E, Peumans M, Lambrechts P, van Meerbeek B. Critical analysis of the influence of different parameters on the microtensile bond strength of adhesives to dentin. J Adh Dent 2008;10:7-16.
57. Proenca JP, Polido M, Osorio E, Erhardt MCG, Aguilera FS, Garcia-Godoy F, Osoprio R, Toledano M. Dentin regional bond strength of self-etch and total-etch adhesive systems. Dent Mater 2007;23:1542-1548.
58. Reis AF, Giannini M, Kavaguchi A, Soares CJ, Line SRP. Comparison of Microtensile Bond Strength to Enamel and Dentin of Human, Bovine, and Porcine Teeth. J Adh Dent 2004;6:117-121.
59. Roulet J-F, van Meerbeek B. Statistics: a nuisance, a tool, or a must? J Adh Dent 2007;3:287-288.
60. Sadek FT, Cury AH, Monticelli F, Ferrari M, Capel Cardoso PE. The influence of the cutting speed on bond strength and integrity of microtensile specimens. Dent Mater 2005;21:1144-1149.
61. Sakaguchi RL, Wiltbank BD, Murchison CF. Prediction of composite elastic modulus and polymerization shrinkage by computational micromechanics. Dent Mater 2004;20:397-401.
62. Sano H, Shono T, Sonoda H, Takatsu T, Ciucchi B, Carvalho R, Pashley DH. Relationship between surface area for adhesion and tensile bond strength – Evaluation of a micro-tensile bond test. Dent Mater 1994;10:236-240.
63. Sattabanasuk V, Shimada Y, Tagami J. The bond of resin to different dentin surface characteristics. Op Dent 2004;29:333-341.
64. Scherrer SS, Cesar PF, Swain MV. Direct comparison of the bond strength results of the different test methods: A critical literature review. Dent Mater 2010;26:e78-e93.
65. Schilke R, Lisson JA, Bauß O, Geurtsen W. Comparison of the number and diameter of dentinal tubules in human and bovine dentine by scanning electron microscopic investigation. Arch Oral Biol 2000;45:355-361.
66. Sengun A, Ünlü N, Ozturk B, Özer F. Microtensile bond strength of two resin composite materials placed with direct and indirect techniques under simulated pulpal pressure. J Adhes Dent 2005;7:197-202.
67. Shono Y, Ogawa T, Terashita M, Carvalho RM, Pashley EL, Pashley DH. Regional measurement of resin-dentin bonding as an array. J Dent Res 1999;78:699-705.
68. Shono Y, Terashita M, Pashley EL, Brewer PD, Pashley DH. Effects of cross-sectional area on resin-enamel tensile bond strength. Dent Mater 1997;13:290-296.
69. Simon Y, Mortier E, Dahoun A, Gerdolle D. Video-controlled characterization of polymerization shrinkage in light-cured dental composites. Polym Test 2008;27:717-721.
70. Soares CJ, Soares PV, Santos-Filho PCF, Armstrong SR. Microtensile specimen attachment and shape finite element analysis. J Dent Res 2008;87:89-93.
71. Watts DC, Cash AJ. Determination of polymerization shrinkage kinetics in visible-light-cured materials: methods development. Dent Mater 1991;7:281-287.
72. Wegehaupt F, Gries D, Wiegand A, Attin T. Is bovine dentine an appropriate substitute for human dentine in erosion-abrasion tests? J Oral Rehabil 2008;35:390-394.
73. Winkler MM, Katona TR, Paydar NH. Finite element stress analysis of three filling techniques for class V light-cured composite restorations. J Dent Res 1996;75:1477-1483.
74. Yamaguchi K, Miyazaki M, Takamizawa T, Tsubota K, Rikuta A. Influence of crosshead speed on micro-tensile bond strength of two-step adhesive systems. Dent Mater 2006;22:420-425.
75. Yeşilyurt C, Bulucu B. Bond strength of total-etch dentin adhesive systems on peripheral and central dentinal tissue: a microtensile bond strength test. J Contemp Dent Pract 2006;7:26-36.
76. Yoshiama M, Carvalho RM, Sano H, Horner JA, Brewer PD, Pashley DH. Regional bond strengths of resins to human root dentine. J Dent 1996;24:435-442.
77. Yoshiyama M, Matsuo T, Ebisu S, Pashley D. Regional bond strengths of self-etching/self-priming adhesive systems. J Dent 1998;26:609-616.
78. Zheng L, Pereira PNR, Somphone P, Nikaido T, Tagami J. Effect of hydrostatic pressure on regional bond strengths of compomers to dentine. J Dent 2000;28:501-508.

Clinical relevance: Composite resin reconstructions of extended areas, such as direct resin veneers or core buildups, if accomplished in one layer extending to the whole area to be bonded, may experience a decrease of bond strength in their periphery.